Physics of Solar Neutron Production: Questionable Detection of Neutrons from the 2007 December 31 Flare

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Abstract.

Spacecraft observations in the inner heliosphere offer the first opportunity to measure 1–10 MeV solar neutrons. We discuss the physics of low-energy neutron production in solar flares and show that, even at interacting-particle energies of 2 MeV nucleon^{-1}, neutrons with energies >10 MeV are produced. On the other hand, a significant fraction of 1–10 MeV neutrons result from interactions of >10 MeV nucleon^{-1} ions in typical flare spectra. We calculate the escaping neutron spectra for mono-energetic and power-law particle spectra at the Sun for the location and observation angle of *MESSENGER* at the time of its reported detection of low-energy neutrons associated with the 2007 December 31 solar flare. We detail concerns about this questionable observation of solar neutrons: 1. the inferred number of accelerated protons at the Sun for this modest M2-class flare was 10× larger than any flare observed to date, 2. the onset and duration of the 'solar' neutron count rate was similar to that of the solar energetic particles (SEPs), and 3. the authors' argument that the SEPs were dominated by electrons and so could not have produced the neutron counts locally in the spacecraft. In contrast we argue that solar energetic protons and α particles, through local neutron production and accidental coincidences, were the source of most of the reported 'solar-neutron' counts.

1. Introduction

Feldman et al. [2010] reported the detection at 0.48 AU of 1–8 MeV neutrons from a solar flare on 2007 December 31. The flare was behind the East limb of the Sun for detectors at Earth, but was well observed by the *MESSENGER* spacecraft on route to Mercury. Although no information was provided for the flux of neutrons, the high statistical significance of the measurement and the 9-hour event duration suggests the presence of a large neutron flux at low energies. Instruments at 1 AU cannot detect neutrons <10 MeV because their travel time from the Sun (>55 min) is long compared to the lifetime of free neutrons ($\sim$ 15 min exponential lifetime). Only measurements made in the inner heliosphere have the realistic potential of detecting these low-energy neutrons. In this paper we discuss the production of low-energy neutrons in solar flares and relate this to the production of higher-energy neutrons and γ rays detected with Earth-orbiting satellites since the late 1970's. A key question in this context is what new information is provided by 1–10 MeV neutron measurements made in the inner heliosphere that cannot be obtained with instruments at 1 AU.

We then evaluate the evidence presented by *Feldman et al.* [2010] and conclude that most, and perhaps all, of the events detected by *MESSENGER* were not due to solar neutrons. We detail instrumental, background, and interpretative issues that may have led to the claimed detection.

2. Low-Energy Neutron Production in Solar Flares

Neutrons are produced in solar flares when accelerated ions interact in the chromosphere. There are a variety of interactions that are important for producing neutrons. The most important reactions are: p-on-H, p-on-^{4}He, α-on-H, α-on-^{4}He, p and α-on-ambient heavy nuclei (direct interactions), and accelerated heavy nuclei-on-H and -^{4}He (inverse interactions) [*Hua et al.*, 2002]. The threshold for neutron production can be <1.0 MeV nucleon^{-1} for interactions involving α-particles and neutron-rich heavy isotopes.

2.1. Calculated Angle-averaged Neutron Spectra at the Sun

We plot calculated angle-averaged neutron energy spectra at the Sun (in the laboratory frame) for incident accelerated particles, normalized to one proton, at energies of 2, 5, 10, and 30 MeV nucleon^{-1} in Figure 1. The calculations have been performed assuming that the accelerated particles, having a coronal abundance [*Reames*, 1995], an α/p ratio of 0.2, and a downward isotropic angular distribution, enter a thick target where they interact. We also assumed that the ambient abundance in the thick target is coronal, but with a ^{4}He/H ratio of 0.1.

The neutron spectra of Figure 1 were calculated using a modification of algorithms originally developed by *Hua et al.* [2002]. Those original algorithms were optimized for calculating >10 MeV neutron spectra observed at Earth resulting from accelerated-particle spectra typically found in solar flares. In that case, the most important neutron-producing reactions are p-on-H, p-on-^{4}He, α-on-H, and α-on-^{4}He at accelerated-particle energies greater than a few tens of MeV nucleon^{-1}. Because of the focus in this paper on low-energy neutrons, we have significantly improved

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14. ABSTRACT
Spacecraft observations in the inner heliosphere offer the first opportunity to measure 1?10 MeV solar neutrons. We discuss the physics of low-energy neutron production in solar flares and show that, even at interacting-particle energies of 2 MeV nucleon−1, neutrons with energies >10 MeV are produced. On the other hand, a significant fraction of 1?10 MeV neutrons result from interactions of >10 MeV nucleon−1 ions in typical flare spectra. We calculate the escaping neutron spectra for mono-energetic and power-law par- ticle spectra at the Sun for the location and observation angle of MESSENGER at the time of its reported detection of low-energy neutrons associated with the 2007 Decem- ber 31 solar flare. We detail concerns about this questionable observation of solar neu- trons: 1. the inferred number of accelerated protons at the Sun for this modest M2-class flare was 10?larger than any flare observed to date, 2. the onset and duration of the ?solar? neutron count rate was similar to that of the solar energetic particles (SEPs), and 3. the authors? argument that the SEPs were dominated by electrons and so could not have produced the neutron counts locally in the spacecraft. In contrast we argue that solar energetic protons and   particles, through local neutron production and acciden- tal coincidences, were the source of most of the reported ?solar-neutron? counts.

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the treatment of low-energy interactions involving heavy elements using the nuclear reaction code TALYS. TALYS (http://www.talys.eu/) is a user-friendly, efficient code simulating nuclear reactions of 1 keV to 250 MeV projectiles using state-of-the-art nuclear models and comprehensive libraries of nuclear data covering all main reaction mechanisms encountered in particle-induced nuclear reactions. These algorithm improvements (along with others) will be discussed fully in a separate paper, but some specific improvements will be mentioned in the following discussion.

In Figure 1a, we show calculated neutron spectra for accelerated particles with initial energies of 2 MeV nucleon^{-1}. At this low energy, the only significant neutron-producing reactions are the exothermic α reactions involving the isotopes ^{13}C, ^{25}Mg and ^{26}Mg (and their inverse interactions) and the low-threshold α reactions involving the isotopes ^{14}N, ^{18}O, ^{22}Ne, ^{29}Si, ^{54}Fe and ^{56}Fe (and their inverse interactions). We note that the yield from the inverse reactions is reduced relative to that of the direct reactions due to the large Coulomb energy losses of heavy elements in the target. Because of the additional energy available in exothermic reactions, even direct reactions can result in neutron energies greater than 10 MeV. For the inverse reactions, the additional total energy associated with the accelerated heavy particles extends this maximum neutron energy to >18 MeV. At this low accelerated-particle energy of 2 MeV nucleon^{-1}, the main modification to the original *Hua et al.* [2002] algorithms is a significant increase in the relative contribution of neutron production due to breakup and stripping of the alpha projectile.

At ion energies of 5 MeV nucleon^{-1} (Fig. 1b), all of the α-heavy interactions (and their inverse reactions) contribute along with the low-threshold p reactions involving ^{13}C, ^{15}N, ^{18}O and ^{22}Ne (and their inverse interactions). The energies of the neutrons emitted in these reactions extend to >30 MeV. For accelerated ion energies of 10 MeV nucleon^{-1} the α-^{4}He channel becomes available along with more of the p-heavy interactions (and their inverse reactions). The α-^{4}He channel produces ∼1–6 MeV neutrons that dominate the low-energy spectrum (Figure 1c); this is the same fusion reaction that produces ^{7}Be which contributes to the ^{7}Li–^{7}Be γ-ray line complex. When the accelerated ions reach 30 MeV nucleon^{-1}, neutron production is open to the α-H and p-^{4}He channels and all of the p- and α-heavy reactions (and their inverse interactions). The spectrum is dominated by the α-^{4}He reaction, extends to several tens of MeV, and is relatively flat from 1–20 MeV (Figure 1d). At these accelerated-particle energies, the main modifications to the original *Hua et al.* [2002] algorithms are (1) particle-energy and target-species dependence of the neutron evaporation temperature and (2) the relative contributions of the evaporation and non-evaporation processes.

We see that even accelerated particles with energies as low as 5 MeV nucleon^{-1} can produce neutrons with energies up to at least ∼ 30 MeV. In addition, accelerated particles of all energies contribute to the flux of 1–10 MeV neutrons. These facts have implications for the uniqueness of low-energy neutron observations in the inner heliosphere.

It is possible that the accelerated particles could have a composition significantly different than coronal material with enhanced helium that we have assumed. For example the γ-ray spectrum from the flare on 1981 April 27 was best fit by an accelerated-particle composition that was similar to impulsive solar energetic particles [*Murphy et al.*, 1991]. The dotted black curves in Figure 1 show the total angle-averaged spectra for this composition. The additional concentration of heavy ions such as Si and Fe increases the numbers of neutrons at high energies, especially for low-energy interacting ions. We note that we have chosen to use a coronal ambient composition that is sometimes required to fit γ-ray data rather than a photospheric composition. This choice provides a moderately increased yield of neutrons due to the enhancement of low-FIP (First Ionization Potential) ions, e.g., Mg, Si, and Fe .

Power-laws in energy are typically used to represent the accelerated-particle spectra in flares. Figure 2 shows the calculated angle-averaged neutron spectrum at the Sun for an accelerated-particle spectrum with a differential power-law index of −4 for one incident proton > 30 MeV. The solid black curve shows the angle-averaged neutron spectrum for the 'coronal' composition used above in the mono-energetic studies presented in Figure 1. We also plot the contributing spectra from the most significant neutron-producing channels. At energies >100 MeV the neutron spectrum is dominated by α-H, α-^{4}He, p-^{4}He, and p-H interactions. We see that the neutron spectrum is flat at energies below 10 MeV. The dotted black curve shows the total neutron spectrum generated by accelerated particles having a composition similar to impulsive solar energetic particles. This spectrum is not significantly different than the spectrum generated by flare-accelerated particles having a coronal composition with enhanced α-particles.

2.2. Calculated Neutron Spectra at the Sun and 0.48 AU

The angular distribution of the ions as they enter the thick target affects the spectrum and angular distribution of neutrons that escape from the Sun. The neutron spectra measured in space are significantly different than the angle-averaged spectra shown in Figures 1 and 2, and depend on the viewing angle. In Figure 3 we show the calculated neutron spectra at the Sun (dotted) and at 0.48 AU (solid), as viewed from an angle of 51° from the radial direction at the flare site (angle that *MESSENGER* observed the 2007 December 31 flare). We show the spectra for the four particle energies and for the power-law spectrum with index −4 calculated for a downward-isotropic distribution of accelerated-particles entering the thick target. We see that the spectra of neutrons escaping the Sun at 51° are significantly steeper than the angle-averaged spectra shown in Figure 1. The additional low-energy neutrons come from downward-moving neutrons that scatter several times, losing energy and changing their direction. Upward-moving neutrons escape with little scattering.

Due to neutron decay depleting the low-energy part of the escaping spectrum, the 1–10 MeV spectrum observed at 0.48 AU is relatively flat for the mono-energetic and power-law particle distributions. The energy peaks of these broad spectra increase moderately with increasing accelerated-particle energy. We see that neutrons can reach surprisingly high energies because of the total energy in ions heavier than He.

3. *In Situ* Detection vs. Remote Detection of Solar-Flare Neutrons

The presence of neutrons in solar flares, even neutrons with low energies, can also be detected remotely through observation of a narrow (few eV) 2.223 MeV γ-ray line emitted in the formation of ^{2}H in the photosphere by neutron capture on H. These neutrons slow down by elastic collisions and are captured at near-thermal energies. The neutron-capture line is the strongest γ-ray line produced in flares and its narrow width makes it one of the clearest signatures of ion acceleration and interaction. However, because it is produced in the photosphere, it is heavily attenuated for flares near the solar limb.

An important question to address is whether remote detection of the 2.223 MeV line with a satellite at Earth is as sensitive to the production of 1–10 MeV neutrons in flares as are *in situ* neutron observations in the inner heliosphere.

The answer depends on the relative sensitivities of the γ-ray and neutron detectors and also on the distance of the neutron detector from the Sun and the longitude of the flare.

At a distance of 0.48 AU the flux of 1–10 MeV neutrons from a flare at a heliocentric angle of 51° is comparable to the flux of 2.223 MeV γ rays at Earth when produced by α-heavy interactions at 2 MeV nucleon^{-1}; for an ion spectrum such as a power law with differential index -4 the flux of 1–10 MeV neutrons at 0.48 AU is only about 30% of the line flux at 1 AU. Typical Earth-orbiting γ-ray line instruments, have effective areas of $\sim$50 cm^2 at 2.223 MeV and therefore are more sensitive to the presence of low-energy neutrons than the $\sim$10 cm^2 *MESSENGER* detector at 0.48 AU where *Feldman et al.* [2010] reported the detection of 1–8 MeV neutrons from the 2007 December 31 flare .

In situ neutron detectors at closer distances to the Sun become more sensitive to 1–10 MeV solar neutrons than modest Earth-orbiting γ-ray line detectors. For example at 30R$_\odot$ the 1–10 MeV neutron flux is between 80 and 20 times the neutron capture line flux at Earth for the range of accelerated-particle spectra discussed above. However, at these close distances to the Sun it is imperative that the detectors can distinguish between neutrons from the Sun and those produced in the spacecraft by solar energetic protons and heavier ions that arrive close in time with the neutrons.

4. Conflict Between Reported Neutron Detection and Solar Physics

We use our understanding of neutron production in flares to assess the reported detection with *Messenger* at 0.48 AU of 1–8 MeV neutrons from the solar flare on 2007 December 31 by [*Feldman et al.*, 2010]. Based on measurements by the X-Ray spectrometer on the spacecraft the flare had an equivalent M2 GOES soft X-ray classification. Using the onset of the neutron signal at *MESSENGER Feldman et al.* [2010] estimated that the maximum solar neutron energy was between 4.8 and 8 MeV under the assumption that the neutrons were produced coincident with the onset times of the X-ray or Type II radio emission, respectively. These times roughly bridge the duration of hard X-rays above the limb of the Sun observed by *RHESSI*. From the limited scatter of the data points we infer that events in the neutron channel were detected with high statistical significance up to 9 hours after the flare. Based on our studies of low-energy neutron production we assess whether the *MESSENGER* spectrometer did indeed detect neutrons from the solar flare.

We first focus on the rapid onset of counts in the 1–8 MeV neutron channel at 01:15 UT at *MESSENGER*. Based on numerous γ-ray line observations, accelerated-ion spectra on closed loops at the Sun can typically be represented by a power law with differential index of $\sim\!-4$ [*Share and Murphy*, 2006]. We see in Figure 3 that the neutron spectrum at 0.48 AU for this particle distribution is relatively flat with strong emission up to several tens of MeV. *Feldman et al.* [2010] state that "... the spacecraft materials are sufficiently massive to soften considerably and attenuate the energy spectrum of neutrons from the Sun." The authors did not quantify this effect on a solar neutron spectrum, such as the one discussed above, passing through the spacecraft. We estimated the extent of this softening using a GEANT4 calculation and assuming that solar neutrons first have to pass through 20 g cm^{-2} of carbon. We find that about 50% of the detected 1–8 MeV neutrons would actually have come from solar neutrons of initially higher energies. These higher-energy neutrons would have arrived earlier than solar 4.8 - 8 MeV neutrons, producing a gradual increase in count rate before 01:15 UT and not the rapid increase that *MESSENGER* observed.

The only way to produce the observed onset is to limit the solar neutron energies to below 10 MeV. From Figure 3 we see that this can occur if the accelerated ions at the Sun only reached energies of $\sim$2 MeV nucleon^{-1} and if their fluxes were extremely high (because of the low neutron yield). If the scattering of low-energy neutrons in the spacecraft before they reach the NS is taken into account, we estimate that the implied flux of flare-accelerated ions would be even 15%–30% higher. We address the plausibility of producing such a flux of low-energy ions at the Sun below.

As we noted earlier, the high statistical significance of the count rate of fast neutrons at *MESSENGER* suggests a high flux of solar neutrons. *Feldman et al.* [2010] did not estimate the flux of solar neutrons that the counting rate implies. Based on the time profile shown in Figure 5 of their paper we estimate that $\sim 2 \times 10^4$ 1–8 MeV fast neutrons would have been counted by *MESSENGER* from 01:15 to 09:00 UT, if we include the extended safe mode period by interpolation. There is no mention of the effective area of the neutron detector in the paper. But if we assume that the efficiency of the 100 cm^2 plastic detector is about 10% then the effective area for 1–8 MeV neutrons would be 10 cm^2, probably accurate to within a factor 3. Thus we estimate that *MESSENGER* observed a total fluence of $\sim 2 \times 10^3$ neutrons cm^{-2}.

For the following calculations we assume that all of the neutrons detected were from the Sun and that there was no modification to the spectrum due to scattering in the spacecraft. We performed the calculations assuming a power-law spectrum of accelerated ions with index -4 for two angular distributions: downward isotropic and fan beam (particles mirroring parallel to the solar atmosphere). For the neutron fluence of 2×10^3 neutrons cm^{-2} we estimate that a total of $(0.8 - 1.3) \times 10^{34}$ protons with energies >30 MeV had to be accelerated in the 2007 December 31 flare. This number of protons is at least an order of magnitude higher than inferred from the 1991 June 4 flare, one of the largest γ-ray line flares observed to date [*Murphy et al.*, 1997].

In a typical γ-ray line flare such a large number of protons would have produced an intense flux of nuclear de-excitation lines and the prominent neutron-capture line. We estimate the strength of the accompanying neutron-capture γ-ray line based on this large number of protons. For the same power-law spectrum and angular distributions we estimate that a detector at Earth would have observed a 2.223 MeV line fluence of $6 \times 10^3 \gamma$ cm^{-2}. This is about a factor of 5 larger than observed in any γ-ray flare observed to date. Observation of such a high flux would have confirmed the *MESSENGER* neutron detection. Because there were no γ-ray measurements made during the 2007 December 31 flare, we cannot explicitly rule out the possibility that this was simply the largest high-energy flare ever observed.

However, a typical M2 soft X-ray flare is not such a prolific source of 2.223-MeV line emission. In observing 300 flares the γ-ray spectrometer on the *Solar Maximum Satellite* barely observed the neutron-capture line from flares with X-Ray classifications of M5 or lower, with 2.223 MeV fluences of only $\sim$ 1-2 γ cm^{-2} [*Vestrand et al.*, 1999], 0.1% of that implied by the *Feldman et al.* [2010] measurement.

Perhaps the flare was atypical in that it only produced neutrons and not nuclear-line and continuum emission above $\sim$300 keV (e.g., the ion spectrum extended only to energies of a few MeV nucleon^{-1}, below the threshold energy for most nuclear line production, and there were no electrons above $\sim$500 keV). However, any interactions producing neutrons would also necessarily produce the neutron-capture line, unless the neutrons were produced well above the chromosphere in which case they could not efficiently be captured on H. Had the neutrons been produced by a mono-energetic 5 MeV nucleon^{-1} flux of accelerated ions, the neutron-capture line flux at Earth would still have been $2.5 \times 10^3 \gamma$ cm^{-2}.

One way to test the plausibility for such an atypical flare is to search for 2.223-MeV line emission outside of times when γ-ray (emission >300 keV) flares have been observed. A conservative limit on the flux in this line during periods with no γ-ray flares is $\sim 7 \times 10^{-5} \gamma$ cm^{-2} s^{-1} based on a study with the SMM spectrometer [*Harris et al.*, 1992]. For the approximate 4-year observing period during which this limit was obtained the total fluence of 2.223 MeV photons was <8000 γ cm^{-2}, at most only 3× higher than the neutron-capture line fluence that would have been observed at Earth from the December 31 flare based on our estimates above. We conclude that it would have been remarkable if *MESSENGER* had detected solar neutrons at the implied level from the 2007 December 31 flare.

5. Possible Explanations for the *MESSENGER* 'Solar Neutron' Observations

Our solar physics arguments above suggest that a solar origin for most of the neutrons observed by *MESSENGER* is implausible. Below we argue that the accompanying solar energetic particle (SEP) event provides two possible explanations for counts classified as neutrons in the *MESSENGER* NS: 1. chance coincidences of SEP events that meet the neutron detection criteria and 2. local production of neutrons by SEPs. Because the flare was behind the East limb of the Sun as viewed from Earth (therefore no magnetic connection to Earth) there was no measurement of SEPs by spacecraft other than those made by *MESSENGER.* We therefore briefly describe how the accompanying SEP event was detected and its characteristics.

5.1. *MESSENGER* SEP Capability and Observations

The *MESSENGER* Energetic Particle Spectrometer (EPS) [*Andrews et al.*, 2007] was designed to detect electrons from 0.025–1.0 MeV and protons from 0.025–3.0 MeV. Distinguishing energetic electrons and ions in the EPS relies on a time-of-flight system that failed prior to the December event. As a result, the 'electron' timelines displayed in Figure 5a of [*Feldman et al.*, 2010] can, in principle, contain a mixture of electrons and ions. In addition, failure of the time-of-flight system also led to an ambiguity in the energy determination of the particles, because what is actually measured is the energy deposition in the instrument. As there is also no anticoincidence element to veto high-energy particles that exit through the back end of the instrument, the EPS is also sensitive to electrons >1 MeV and protons with energies >3 MeV. As discussed below, this sensitivity to high-energy particles affects the authors' arguments that the EPS was primarily responding to low-energy electrons.

Elements of the neutron spectrometer (NS) can also be used as solar energetic particle detectors [*Feldman et al.*, 2010]. The lithium glass (LG) thermal neutron detectors are sensitive to electrons from 0.3 to 2 MeV and to protons <30 MeV. Double coincidences between a single LG and the borated plastic (BP) fast neutron detector provide the capability for detecting 2 to 20 MeV electrons and 30 to 120 MeV protons. Triple coincidences between the BP detector and two LG detectors on either side provide sensitivity to electrons >20 MeV and protons >120 MeV.

Assuming the double and triple coincidence rates are due to energetic protons, and not chance coincidences or electrons, we can estimate the proton spectrum just before the safe hold. Using the geometric factors given in the paper we infer that the flux of 30–120 MeV protons was about 4.6 cm^{-2} s^{-1} sr^{-1} and of >120 MeV protons was about 1.1 cm^{-2} s^{-1} sr^{-1}. Assuming a power-law spectrum the ratio of these two fluxes implies a differential index of −2.2. A spectrum as hard as this has implications for local neutron production that we discuss §5.2.2. Such neutron production requires that ions were a significant component of the SEPs, in contrast to the arguments by *Feldman et al.* [2010] that the SEPs were dominated by electrons. We address evidence for the composition of the SEPs below.

Particle rates measured by the EPS, and double and triple coincidences in the NS, increased at ∼01:15 UT. There was no sign of velocity dispersion in the EPS energy channels as would be expected if it were detecting only <1 MeV solar electrons [*Feldman et al.*, 2010]. However, this lack of detectable dispersion could be due to particles with energies above the nominal pass-bands for registering in the EPS, as we discussed above. In fact the presence of such high-energy electrons and/or protons is implied by the simultaneous onsets of the EPS, and the double and triple coincidence rates in the NS. The authors do not address this possibility but attempt to resolve the conundrum posed by the dispersion-free EPS onsets by invoking the tangential discontinuity (TD) in the magnetic field observed by *MESSENGER* about 5 minutes before the EPS onset. That is, prior to crossing the TD, the spacecraft was not on magnetic field lines connected to the flare site where the particles were produced. After crossing the TD, *MESSENGER* encountered field lines already populated with flare-generated charged particles of various energies; hence the simultaneous onset in the EPS electron channels and the double and triple coincidences in the NS.

Feldman et al. [2010] further argued that particles detected from the onset of the SEP event until the safe hold mode had to be electrons because protons with energies below the ∼1 MeV upper limit for the EPS could not arrive by that time. However, because of the failure in the time-of-flight system and lack of an anti-coincidence detector, the EPS is sensitive to protons well above 1 MeV which would have arrived by that time. Furthermore, it is difficult to understand why low-energy electrons could escape from the flare site while so few of the $\sim 10^{34}$ protons needed to explain the neutron observations could not. Whether or not solar neutrons were observed, the authors' conclusion that the SEP event was dominated by electrons appears to be unfounded.

5.2. Two Explanations for the *MESSENGER* Neutron Measurements

A troubling characteristic of the time profile of the fast-neutron flux is that it was remarkably similar to that of the SEP fluxes during both onset and decay phases of the event (see Figures 4 and 5 in *Feldman et al.* [2010]). The onset times of the neutron and particle events were consistent with one another to within 1–2 minutes and as the authors point out, there are "similarities of their decay phases." This raises concerns that the events ascribed to neutrons may be related to the solar energetic particles. The are two plausible ways in which this can occur: chance coincidences due to the high rate of SEPs and secondary interactions of the SEPs producing neutrons in the material of the spacecraft, including its fuel tanks.

5.2.1. SEP Chance Coincidences Could Emulate Neutrons

The instruments on *MESSENGER* were primarily designed for planetary studies. It is not clear how well they performed when encountering the high-particle rates in the SEP event. The NS detects fast neutrons in the borated plastic detector. The BP distinguishes neutrons from particle events by a coincidence between the prompt pulse in the plastic from neutron-energy loss and the delayed pulse from α particles emitted in the ^{10}B(n,α)^{7}Li reaction. The authors demonstrated that neutrons were detected by showing that both the delay and spectrum of the α particles were consistent with emission from this reaction (see Figure 7 in *Feldman et al.* [2010]). These comparisons were made after

they first removed chance coincidences between unrelated particle events in the ~ 25 μs acceptance window for neutrons [*Goldsten et al.*, 2007]. Indeed, the time profile in Figure 7a [*Feldman et al.*, 2010] shows evidence for this subtraction in the large uncertainties that appear just above delays of 6 μs in the BP.

It is not clear from *Feldman et al.* [2010] if such chance coincidences occurring within the ~ 25 μs acceptance window were subtracted from the fast neutron rates shown in Figures 4 and 5 of the paper. The probability that two particle events occur during a given time period is given by the Poisson probability: $P_2 = m^2 \times (e^{-m}/2!)$, where m is the mean number of events in the time interval. We do not know what the singles particle rate was in the BP or how restrictions on the allowable energies of the initiating and α-particle pulses affect the neutron count rate. We do know that the double coincidence rate (between the LG and BP) was $\sim$1000 Hz after the safe hold period and that the singles rate in the exposed LG detector at this time was $\sim 10^4$ Hz. Assuming a BP singles rate of 1000 Hz (lower limit), m=0.025 and $P_2 = 3 \times 10^{-4}$ for each 25 μs bin; this yields a total chance coincidence rate of 0.3 Hz, only a factor of 5 below the neutron rate observed just after the safe hold.

Thus, it is possible that a large fraction of the fast neutron rate could be due to chance coincidences. If the authors had corrected the fast neutron rate for chance coincidences the uncertainty in the neutron fluxes should have been significantly larger than inferred in Figures 4 and 5 of the paper.

5.2.2. Secondary Neutrons Produced by SEP Interactions

The NS cannot distinguish between primary solar and secondary spacecraft neutrons. *Feldman et al.* [2010] themselves qualified their claims for a solar origin of the neutrons with concerns that some of the neutrons may have been produced by interactions in the spacecraft by protons in the SEP event. Based on calculations, *Feldman et al.* [2010] concluded that the number of secondary neutrons from SEP interactions in the late stage of the observations (about 3 hours after their initial detection) was at most 20% of the total number of fast neutron counts. The authors maintained that this was likely to be an upper limit because they had concluded that electrons dominated the SEPs. Because of the failure of the TOF in the EPS, there is no direct evidence that the EPS timelines do not contain a mixture of electrons and high-energy protons. The authors appeal to an indirect argument to reject the presence of high-energy protons. Specifically, they argue that if there were such high-energy protons, there would have been lower-energy protons, below 1 MeV. The later arrival of these low-energy protons would have distorted the EPS timelines in ways that are not observed. Although, this assertion may be true, its qualitative nature, without quantitative modeling to back it up, renders it less than compelling our opinion.

The authors' estimate that secondary neutrons could contribute at most 20% to the observed fast neutron rate was based on a complex analysis of geometric factors for galactic cosmic rays and SEPs. They assumed that all the particles detected by the double coincidence between the LG and BP were protons and the SEPs had a spectrum that followed a power law with differential index of -3.5, in contrast to the index of about -2.2 that we inferred above from a comparison of the double and triple coincidence rates. This -3.5 index was determined from measurements of the 2002 February 20 SEP event observed at 1 AU discussed by *Feldman et al.* [2010]. Our study indicates that the peak proton flux $>$30 MeV in the 2002 February event was $\sim$2 cm^{-2} s^{-1} sr^{-1}, comparable to that of the 2007 December 31 event ($\sim$1 cm^{-2} s^{-1} sr^{-1} corrected to 1 AU). The lack of clear evidence for protons $>$120 MeV in the February event is consistent with its steeper spectrum.

Because the SEP spectrum in the December event appears to be harder than assumed by the authors, we re-evaluated secondary neutron production using the neutron generation curve in Figure 8 of the *Feldman et al.* [2010] paper. We find that for the harder SEP spectral index, -2.2, secondary neutrons could contribute $\sim$40% to the observed fast neutron rate.

Low-energy solar energetic α particles interacting with the spacecraft can also produce secondary neutrons. This source of secondary neutrons was not considered by *Feldman et al.* [2010]. As we see in Figure 1 α-particle interactions $<$10 MeV nucleon^{-1} on heavy nuclei are the dominant sources of 1–10 MeV neutrons. Significant fluxes of α particles have been observed in impulsive events associated with low M-class X-ray flares [*Mason et al.*, 2002]. Interestingly, the onset time for neutrons and charged particles in Figure 4b of *Feldman et al.* [2010] are consistent with the arrival of 5 MeV nucleon$^{-1}\alpha$ particles. In addition durations of several hours for $\sim$MeV nucleon^{-1} ions in impulsive SEP events are quite typical and similar to the duration of the neutron event. Detailed calculations, similar to those done by the authors for protons, are required to determine the fraction of fast neutrons observed by *MESSENGER* that could be due to secondary neutrons from solar energetic α-particle interactions.

We conclude that secondary neutrons from SEP interactions in the spacecraft contributed significantly more than 20% to the observed fast neutron rate.

6. Summary and Discussion

The reported detection of 1–8 MeV neutrons from the 2007 December 31 solar flare by the *MESSENGER* NS at 0.48 AU [*Feldman et al.*, 2010] prompted us to both study the physics of low-energy neutron production in flares and evaluate the evidence for solar neutrons. We conclude that the reported detection was flawed.

We have discussed the various neutron production channels from ion interactions in flares. Alpha-particle interactions dominate low-energy neutron production for incident particle energies below about 30 MeV nucleon^{-1} for plausible accelerated ion and ambient compositions. At higher incident energies, proton interactions contribute a growing fraction of the 1–10 MeV neutrons produced in solar flares. Due to exothermic reactions and the additional total energy associated with accelerated heavy ions, neutrons with energies above 10 MeV are produced even for ions with energies of 2 MeV nucleon^{-1}. In addition ions with energies of tens of MeV and above are prolific producers of these low-energy neutrons. Thus we know of no particle interaction that produces only 1–8 MeV neutrons. We have shown that down-scattering in the spacecraft of these higher-energy solar neutrons from any plausible solar spectrum would have produced fast neutron count rates that increased earlier than observed.

Because low-energy neutrons are emitted roughly isotropically in the lab frame, many will move into higher densities of the solar atmosphere and produce the strong 2.223 MeV line when they form deuterium. If neutrons had been detected at the level implied by the *MESSENGER* observation of the 2007 December 31 flare, neutron-capture γ rays would have been easily detected by instruments at Earth had the flare not been behind the solar limb. Without such a confirmation we can only use the *MESSENGER* data themselves to assess the plausibility of the reported neutron detection. We have shown that the intense neutron signal observed by the NS over the 9-hr observation period, if solar, required the acceleration of $\sim 10^{34}$ protons $>$30 MeV for a typical flare spectrum of ions. This number of protons is a factor of ten larger than that estimated for the largest γ-ray line flare observed to date, the 1991 June 4 flare in which $\sim 7 \times 10^{32}$

protons were inferred [*Murphy et al.*, 1997]. The December 31 event was classified only as a GOES M2 flare, a class of flare that is typically not a prolific producer of γ rays or neutrons; in contrast to the June 4 flare that was an X12+ flare.

Typical X-ray flares with classifications lower than M5 produce neutron-capture line fluences only ∼0.1% of that implied by the *Feldman et al.* [2010] measurement. The 2002 February 20 event which the authors compare to the 2007 December 31 flare was a GOES M6 X-ray event with photon emission only extending up to ∼25 keV in measurements made by RHESSI just after the peak. There was no evidence for significant γ-ray emission that is typically associated with the production of neutrons in this flare. The implied 2.223 MeV line fluence from the December 31 flare was also comparable to the upper limit in the solar line fluence observed by the *SMM* spectrometer over a period of four years, excluding γ-ray flares.

These physical arguments raise serious concerns about the reported detection of solar neutrons in the 2007 December 31 flare. We have attempted to understand how the *MESSENGER* NS data might have been attributed to solar neutrons. We first note that the instrument was designed for planetary studies and may have had difficulties with the high data rates encountered during the accompanying SEP event. The fact that the rise of this intense SEP event was coincident with the rise of the 1–8 MeV neutron signal is a serious concern.

There are two ways in which the SEPs may have mimicked the arrival of solar neutrons: chance coincidences and local neutron production. It was not clear in their paper if *Feldman et al.* [2010] had subtracted the large SEP chance-coincidence rate in the NS from the raw neutron measurements or if it was taken into account in assessing the significance of the observation. We have also shown that solar energetic proton interactions in the spacecraft would have produced a large fraction of the apparent solar neutron flux for a hard spectrum; e.g., a power law with differential index −2.2. Such a hard spectrum of SEPs is consistent with the double and triple coincidence rates observed by the NS detectors. We have also discussed the significant role that low-energy α particles can play in the local production of neutrons. Alpha particles are an important component of impulsive SEPs associated with M-class flares.

Feldman et al. [2010] argue that the SEP event was predominately composed of electrons that could not produce secondary neutrons. We have shown that a failure in the EPS detector precludes such a conclusion. The authors attribute the sharp rise in the SEP rate to passage of the spacecraft through a tangential discontinuity in the magnetic field that allowed flare-accelerated electrons to reach *MESSENGER*. However, the neutron onset in the NS occurs simultaneously with the onset of charged particles in the EPS. Since neutrons are unaffected by magnetic fields, this coincidence must be accepted as a remarkable accident if the neutrons came from the Sun. Although there is evidence for such a discontinuity in magnetometer data at that time, the level of the discontinuity was similar to those observed at other times during the observation.

In any case there is a clear inconsistency in the authors' argument about the composition of the SEPs and their flare origin. We have shown that if solar neutrons had indeed been detected at the level inferred from the observations, the number high-energy protons at the flare site would have been ten times larger than inferred from any γ-ray flare observed to date. It would be surprising for this intense flux of protons to be trapped at the Sun while the accelerated electrons were able to escape.

When all of these concerns are taken into account, we conclude that the reported detection of 1–8 MeV neutrons from the 2007 December 31 flare at the inferred level is, at best, highly questionable. With the inconsistencies in the interpretations and the unusual and unprecedented requirements on solar physics to produce the claimed observations, we suggest a simpler explanation of the measurement: that the 'neutron' signal registered by *MESSENGER* was of local origin—a combination of (1) accidental coincidences, and (2) local neutron production by solar energetic protons and α particles.

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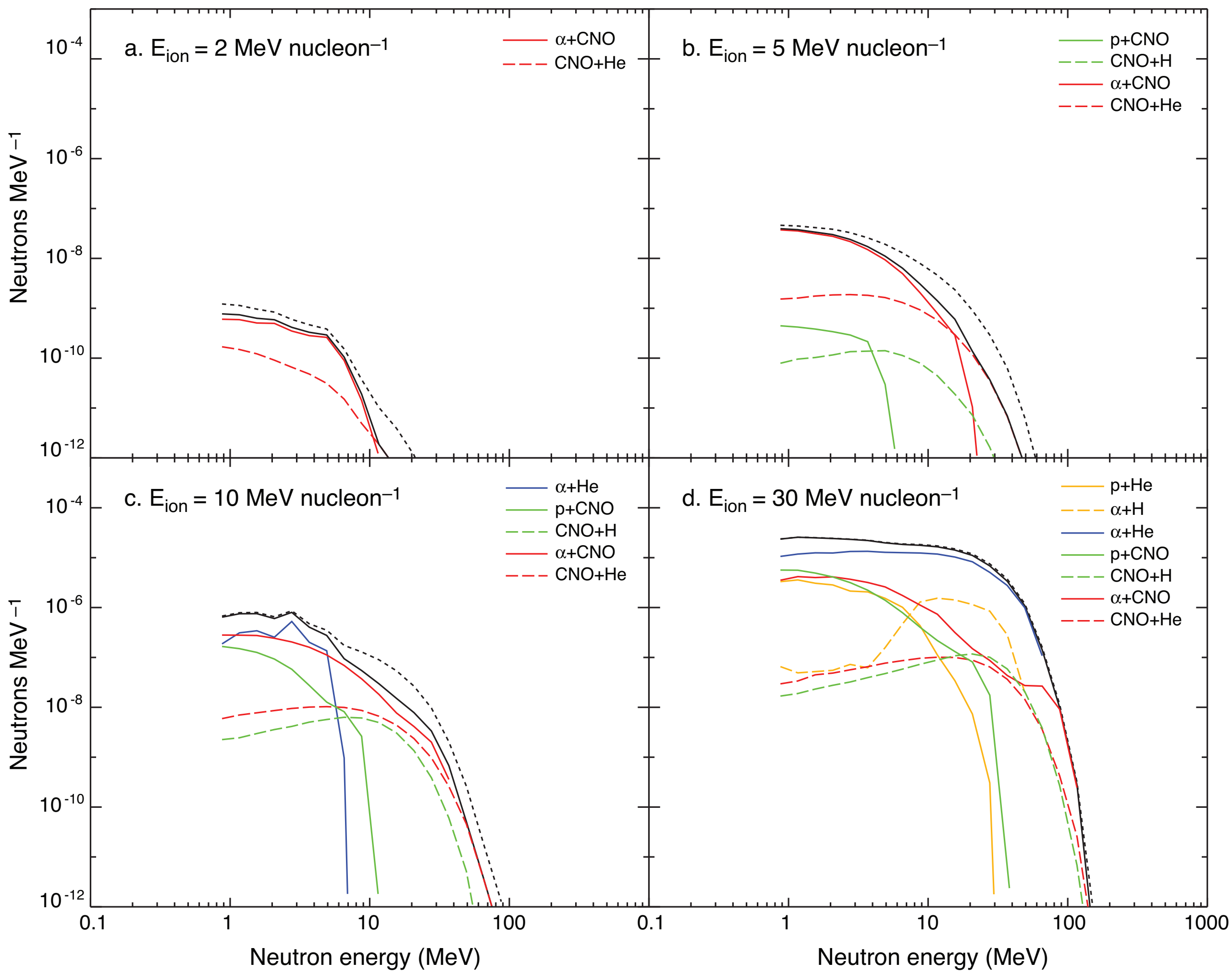

Figure 1. Calculated angle-averaged neutron spectra at the Sun for incident accelerated particles normalized to one proton and having a coronal composition with α/p = 0.2 (solid black). Spectra from the different production channels are also shown. 'CNO' refers to all nuclear species heavier than He. Calculated spectra for accelerated ions with an impulsive SEP composition (dotted black).

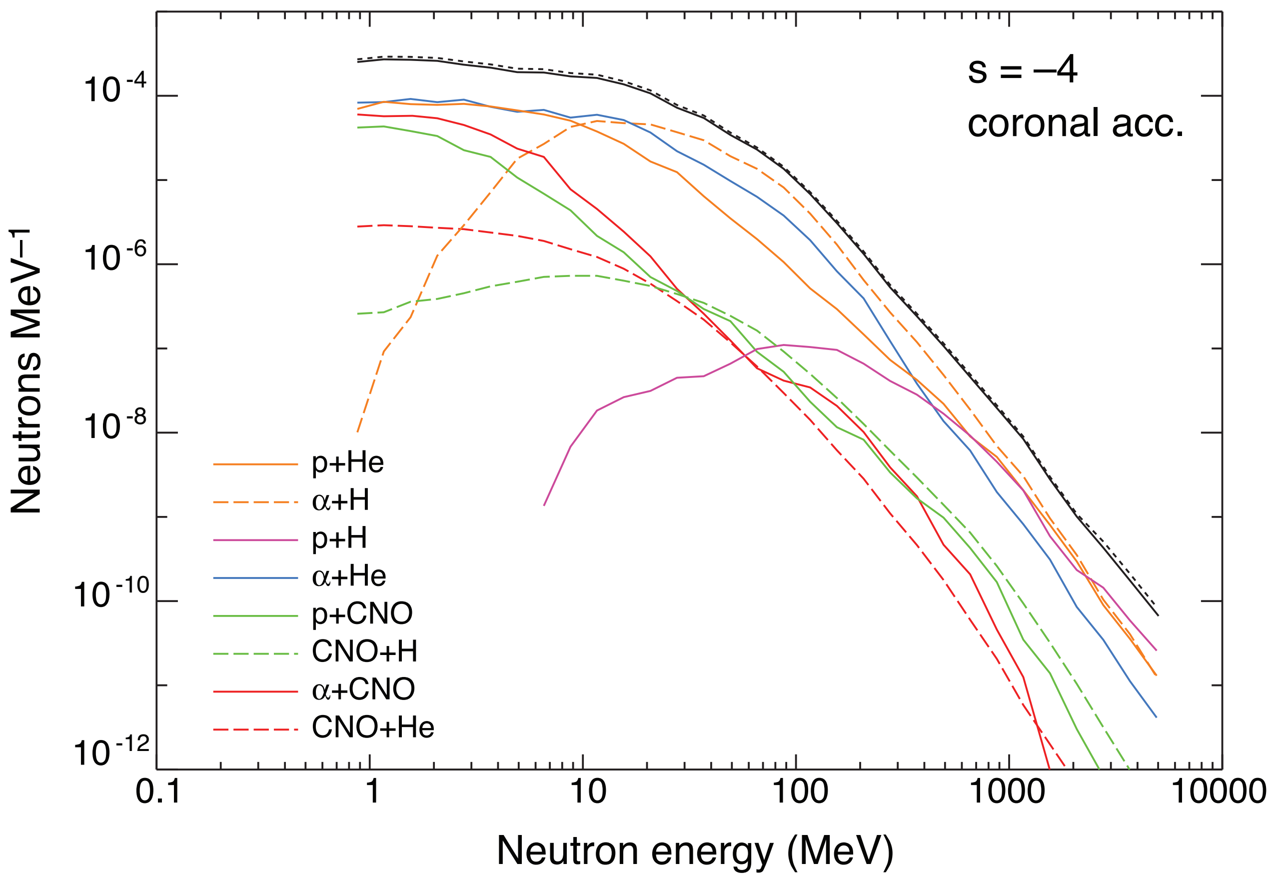

Figure 2. Calculated angle-averaged neutron spectrum at the Sun for accelerated particles following a power-law spectrum with index -4 normalized to one incident proton > 30 MeV and having a coronal composition with α/p = 0.2 (solid black). Spectra from the different production channels are also shown. 'CNO' refers to all nuclear species heavier than He. Calculated spectrum for accelerated ions with an impulsive SEP composition (dotted black).

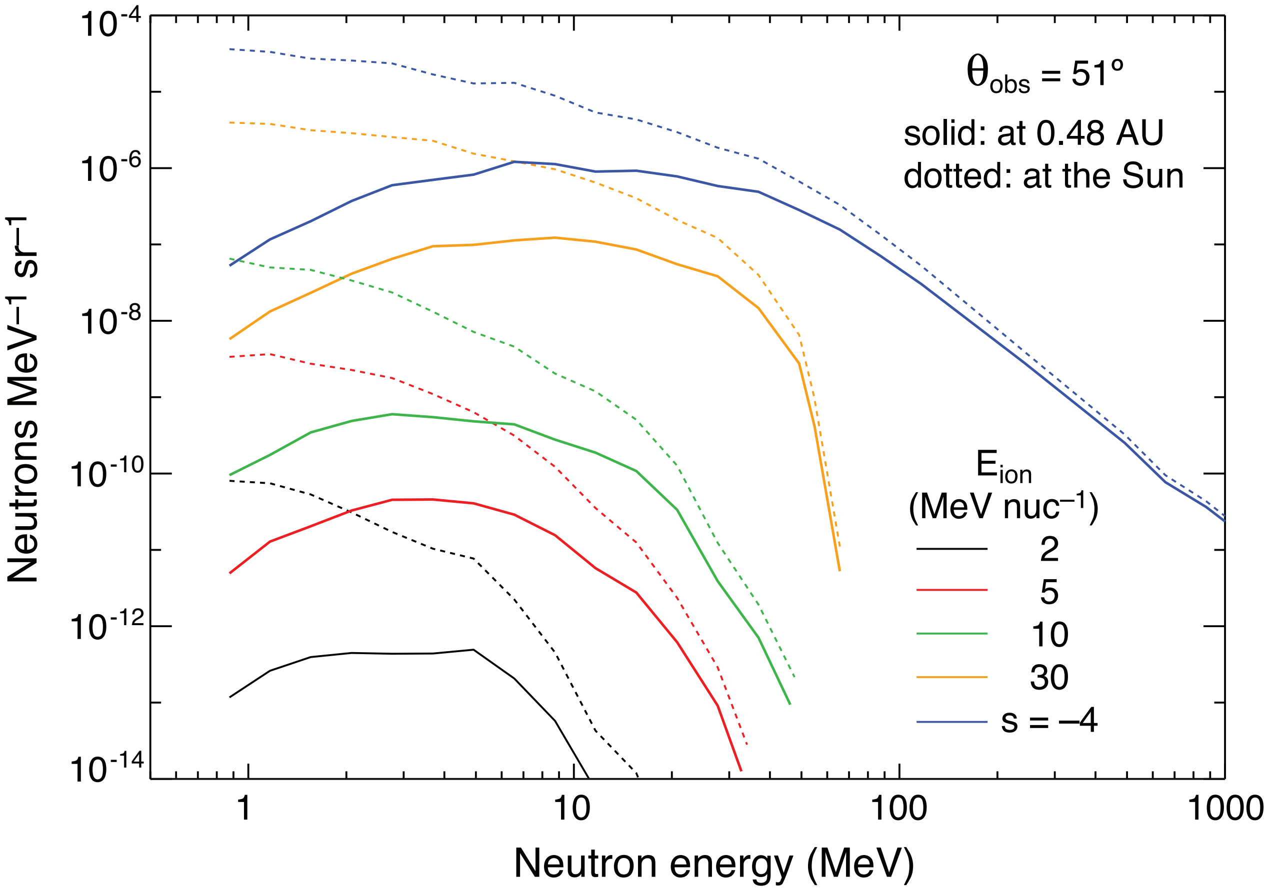

Figure 3. Calculated neutron spectra at 0.48 AU observed at 51° for monoenergetic particles (normalized to one proton at that energy) and for particles with s = −4 power-law spectra (normalized to one proton >30 MeV) having a coronal composition with α/p = 0.2 (solid). 'CNO' refers to all nuclear species heavier than He. Calculated spectra at the Sun (dotted).